

QUARK-GLUON PLASMA SIGNATURES IN NUCLEUS-NUCLEUS COLLISIONS AT CERN SPS

Mark I. Gorenstein

Bogolyubov Institute for Theoretical Physics, Kyiv, Ukraine

Abstract

Two signatures of the quark-gluon plasma – strangeness ‘enhancement’ and J/ψ ‘suppression’ – in nucleus-nucleus collisions at the SPS energies are critically discussed.

I. Introduction

A discovery of the quark-gluon (QGP) in nucleus-nucleus (A+A) collisions at CERN SPS was recently announced [1]. The present status of this discovery is still somewhat uncertain and is right now vigorously debated. The data on the transverse energy of secondary particles in central Pb+Pb at 158 A·GeV and assumed early stage collision geometry lead to the estimate of the initial energy density $\varepsilon_{in} = 3 \div 4$ GeV/fm³. The state of matter at this high energy density is expected to consist of the deconfined quarks and gluons. Are there evidences of the transient QGP state in the measured data?

II. Chemical and Thermal Freeze-Out

The yields of different hadron species, π^+ , π^- , K^+ , K^- , p , \bar{p} , ... , Ω , $\bar{\Omega}$, have been measured in A+A collisions at the SPS energies. The measured hadron multiplicities are consistent with a simple picture of the statistical hadronization with chemical freeze-out temperature $T_H = 170 \pm 10$ MeV (see Ref.[2]). The temperature T_H is close to the expected value for the phase transition between hadron matter and QGP. It suggests a possibility to associate the chemical freeze-out in A+A collisions at the SPS energies with QGP hadronization transition.

The data on hadron transverse momentum spectra in Pb+Pb collisions at 158 A·GeV exhibit the exponential behavior $\exp(-\sqrt{m_i^2 + p_\perp^2}/T_i)$ with approximately linear dependence of the slope T_i on particle mass m_i . The explanation of these data requires a strong transverse collective flow, $\langle v_\perp \rangle \cong 0.5$, and low thermal freeze-out temperature $T_f \cong 120$ MeV (see Ref.[3]).

The data on hadron multiplicities and momentum spectra give no direct information about the QGP existence. These hadron observables are formed after (or during) the QGP hadronization. Any real probe of the QGP must be present in the early stage of the reaction (before hadronization) and retain the signature of the deconfined matter properties throughout the confinement transition and the subsequent hadron matter evolution. Real and virtual photons are emitted at all stages of the system evolution. They leave the medium without strong interactions and therefore reflect the matter properties at the time they were created. Thermal emission of the photons and lepton pairs can be used

to determine the matter temperature at different stages of A+A collision. The crucial problem for this probe is however the subtraction of the background effects: the measured spectra are dominated at high photon momenta or dilepton mass by hard primary reactions and at low momenta or masses by hadron decay products. Thermal photons or dileptons emission from the QGP has so far not been identified.

In what follows we discuss to main signals of the QGP: strangeness ‘enhancement’ and J/ψ ‘suppression’.

III. Strangeness ‘Enhancement’

The idea of strangeness enhancement as a QGP signal was formulated a long time ago [4]. It was based on the estimate that the strangeness equilibration time in QGP is of the same order (≈ 10 fm/c) as the expected life time of the fireball formed in A+A collisions. Thus in the case of QGP creation the strangeness is expected to approach its equilibrium value in QGP. This equilibrium value is significantly higher than the strangeness production in nucleon–nucleon (N+N) collisions. Strangeness production in secondary hadronic interactions was estimated to be negligible small. Therefore, if QGP is not formed, the strangeness yields would be expected to be much lower than those predicted by equilibrium QGP calculations. Thus at that time a simple and elegant signature of QGP creation appeared: *a transition to QGP should be signaled by an increase of the strangeness production to the level of QGP equilibrium value*. In an actual study of strangeness production, due to experimental and theoretical reasons, it is convenient to analyze strangeness to pion ratio:

$$E_s = \frac{\langle \Lambda \rangle + \langle K + \bar{K} \rangle}{\langle \pi \rangle} . \quad (1)$$

In the QGP picture the ratio can be estimated from the equilibrium strangeness to entropy ratio using common assumption of isentropic expansion.

The confrontation of these expectation with the data was for the first time possible in 1988 when the preliminary surprising results from S and Si beams at SPS and AGS were presented. The experiment NA35 reported that in central S+S collisions at 200 A·GeV the strangeness to pion ratio is 2 times higher than in N+N interactions at the same energy per nucleon. Even larger enhancement (a factor of about 3) was measured by E802 in Si+A collisions at AGS. Recent data on central Au+Au collisions at low AGS energies completed the picture: strangeness enhancement is observed at all energies, it is stronger at lower energies than at the SPS energy. This enhancement goes to infinity at the threshold energy of strange hadron production. Thus the AGS measurements of strangeness enhancement larger than that at SPS showed clearly that *the simple concept of strangeness enhancement as a signal of QGP is incorrect*.

In fact, for the chemical freeze-out parameters, temperature T and baryonic chemical potential μ_b , found for the SPS energies the strangeness to entropy ratio is larger in the equilibrium hadron gas (HG) than in the equilibrium QGP. To estimate the strangeness to entropy ratio let us consider the quantity

$$R_s \equiv \frac{N_s + N_{\bar{s}}}{S} , \quad (2)$$

where N_s and $N_{\bar{s}}$ are the numbers of strange quarks and antiquarks, and S is the total entropy of the system. In the QGP we use the ideal gas approximation of massless u -, d -(anti)quarks and gluons, strange (anti)quarks with $m_s \cong 150$ MeV. For the HG state the values of N_s and $N_{\bar{s}}$ are calculated as a sum of all s and \bar{s} inside hadrons, and S is the total HG entropy. The behavior of R_s (2) for the HG and QGP is shown in Fig. 1 as a function of T for $\mu_B = 0$. At temperatures $T \geq 200$ MeV one finds in the QGP an almost constant value of R_s which is smaller than the corresponding quantity in the HG. The total entropy as well as the total number of strange quarks and antiquarks are expected to be conserved approximately during the hadronization of QGP. This suggests that the value of R_s at the HG chemical freeze-out should be close to that in the equilibrium QGP and smaller than in the HG at chemical equilibrium. Therefore, the strangeness *suppression* in the HG would become a signal for the formation of QGP at the early stage of A+A collision at the CERN SPS energies.

The statistical model of the early stage of A+A collisions [5] leads to the following predictions for strangeness production (see Fig. 2):

1. A non-monotonic (or kinky) collision energy dependence of the strangeness to pion ratio (1). A creation of the QGP in the energy region between the AGS and SPS would change an initial fast increase of this ratio in equilibrium hadron gas by a *decrease* to the level expected in equilibrium QGP. New preliminary data in Pb+Pb at 40 A·GeV support this conclusion [6].
2. Very similar strangeness to pion ratio is predicted for SPS, RHIC and LHC energies as strangeness/entropy ratio in the QGP is almost independent of temperature (collision energy).

IV. J/ψ ‘Suppression’

A standard picture of J/ψ production in hadron and nuclear collisions assumes a two step process: the creation of $c\bar{c}$ pair in hard parton collisions at the very early stage of the reaction and the subsequent formation of a bound charmonium state. Matsui and Satz proposed [7] (see also [8] and references therein) to use J/ψ as a probe for deconfinement in the study of A+A collisions. They argued that in QGP color screening dissolves initially created J/ψ mesons into c and \bar{c} quarks which at hadronization form open charm hadrons. As the initial yield of J/ψ is believed to have the same A-dependence as the Drell–Yan lepton pairs, the measurement of a weaker A-dependence of final J/ψ yield (J/ψ ‘suppression’) would signal charmonium absorption and therefore creation of QGP. The measured A-dependence of J/ψ production in p+A is weaker than A^1 (approximately $A^{0.9}$). It was suggested that this J/ψ suppression is due to absorption in target nucleus. The data on oxygen and sulphur collisions on nuclei at 200 A·GeV also indicated presence of the considerable suppression. To improve a fit of the data a new source of J/ψ absorption was introduced: the absorption on hadronic secondaries (‘comovers’). Finally in central Pb+Pb collisions at 158 A·GeV the measured suppression is significantly stronger than expected in the models including nuclear and comover suppressions. This ‘anomalous’ J/ψ suppression is now interpreted as an evidence of QGP creation in Pb+Pb collisions at CERN SPS.

In Ref. [9] a mechanism of thermal J/ψ production was suggested. The thermal yield

of J/ψ mesons is given by

$$\begin{aligned}\langle J/\psi \rangle &= \frac{(2j+1)V}{2\pi^2} \int_0^\infty \frac{k^2 dk}{\exp[(k^2 + m_\psi^2)^{1/2}/T_H] - 1} \\ &\cong (2j+1)V \left(\frac{T_H m_\psi}{2\pi^2} \right)^{3/2} \exp\left(-\frac{m_\psi}{T_H}\right),\end{aligned}\tag{3}$$

where $j = 1$ and $m_\psi \cong 3.1$ GeV are the spin and mass of the J/ψ meson and T_H is the hadronization temperature. The total system volume V is the sum of the proper volume elements at the hadronization stage. Both T_H and V parameters are already fitted to the data on hadron yields. Therefore, Eq. (3) introduces no additional free parameter. The ratio $\langle J/\psi \rangle / \langle h^- \rangle$ is known experimentally as a function of the mean number of nucleons N_P participating in the interaction. The data exhibits approximately constant value of the ratio for p+p and A+A interactions including the most recent results on centrality selected Pb+Pb collisions. The $\langle J/\psi \rangle$ and $\langle h^- \rangle$ denote the mean multiplicities of J/ψ mesons and negatively charged hadrons (more than 90% are π^- mesons), respectively. A simple assumption of J/ψ thermal production at the hadronization stage explains naturally the scaling behavior of $\langle J/\psi \rangle / \langle h^- \rangle$ ratio and also the absolute number of the produced J/ψ mesons for $T_H \cong 180$ MeV. Within the hard production mechanism the observed independence of the $\langle J/\psi \rangle / \langle h^- \rangle$ ratio of the collision type results as an *accidental* cancelation of several large effects: large initial J/ψ multiplicity in A+A collisions is reduced by a sequence of absorption processes always (‘accidentally’) to the scaling (constant) value of the $\langle J/\psi \rangle / \langle h^- \rangle$ ratio.

In the statistical model of Ref.[9] the J/ψ yield is **independent** of the open charm yield. Recently the statistical coalescence model was introduced for the charmonium production in Ref.[10]. Similar to the statistical model [9], the charmonium states are assumed to be formed at the hadronization stage. However, they are produced as a coalescence of created earlier c - \bar{c} quarks and therefore the multiplicities of open and hidden charm hadrons are **connected** in that model [10]. The numbers of c - \bar{c} quarks are restricted to the values expected within the pQCD approach. It seemed to be larger than the equilibrium HG result. This requires the introduction of a new parameter in the HG approach [10] – the charm enhancement factor γ_c (it was denoted as g_c in Ref.[10]). This is analogous to the introduction of strangeness suppression factor γ_s [11] in the HG model, where the total strangeness observed is smaller than its thermal equilibrium value. Within this approach the open charm hadron yield is enhanced by a factor γ_c and charmonium yield by a factor γ_c^2 in comparison with the equilibrium HG predictions.

The statistical coalescence model with an exact charm conservation is formulated in Ref.[12]. The canonical ensemble suppression effects are important for the thermal open charm yield even in the most central Pb+Pb collisions at the SPS energies. These suppression effects become crucial when the number of participants N_p decreases. From the J/ψ multiplicity data in Pb+Pb collisions at 158 A·GeV the open charm yield is predicted: $N_{cc}^{dir} = 0.4 \div 0.7$ in the most central collisions. It is surprisingly close to the estimate $N_{cc}^{eq} \cong 0.5$ [10] for the chemical equilibrium value in the quark-gluon plasma before hadronization. The model predicts also the N_p -dependence of the open charm and the yields of individual open charm states. These predictions of the statistical coalescence model (the open charm yield has not been measured in Pb+Pb) can be tested in the near

future (measurements of the open charm are planned at CERN). Such a comparison will require to specify more accurately the $\langle J/\psi \rangle$ data.

The charm enhancement factor γ_c found from the $\langle J/\psi \rangle$ data appears to be not much different from unity. Therefore, both the statistical model of Ref.[9] and the statistical coalescence model [10, 12] lead to similar results for the J/ψ yield. The predictions of these two models will differ greatly at RHIC energies: according to [9] the J/ψ to pion ratio is expected to be approximately equal to its value at the SPS, but according to the statistical coalescence model this ratio should increase very strongly.

V. Conclusions

- The matter with energy density $\varepsilon_{in} = 3 \div 4 \text{ GeV/fm}^3$ is created at the early stage of central Pb+Pb collisions at CERN SPS, most probably in the QGP state.
- The hadronization of the QGP leads to the locally equilibrium hadron gas state with temperature parameter $T_H = 170 \pm 10 \text{ MeV}$.
- The deconfinement phase transition is expected to occur at the collision energies between AGS and SPS where the strangeness to entropy (pion) ratio in the equilibrium confined (hadron) matter is higher than in the QGP. It leads to non-monotonic (or kinky) dependence of the strangeness to pion ratio on collision energy [5] (see Fig. 2).
- Statistical hadronization of the QGP is probably an important source of J/ψ production [9]. This fact would open a new look at J/ψ ‘suppression’ signal of the QGP. The assumption of J/ψ thermal production at the hadronization stage explains naturally the scaling behavior of $\langle J/\psi \rangle / \langle h^- \rangle$ ratio and also the absolute number of the produced J/ψ mesons.
- The statistical model of Ref.[9] and the statistical coalescence model [10, 12] lead to similar results for the J/ψ yield at the SPS energies. However, the predictions of these two models will differ at RHIC energies: according to [9] the J/ψ to pion ratio is expected to be approximately equal to its value at the SPS, but according to the statistical coalescence model this ratio should increase very strongly.

Acknowledgments. I am thankful to F. Becattini, P. Braun-Munzinger, K.A. Bugaev, M. Gaździcki, L. Gerland, W. Greiner, A.P. Kostyuk, L. McLerran, I.N. Mishustin, G.C. Nayak, K. Redlich, J. Stachel and H. Stöcker for useful comments and discussions. The financial support of DAAD Germany is acknowledged. The research described in this publication was made possible in part by Award # UP1-2119 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF).

References

- [1] U. Heinz and M. Jacob, *Evidence for a New State of Matter: an Assessment of the Results from the CERN Lead Beam Program*, nucl-th/0002042 (2000); CERN Courier No. 3, page 13, April 2000.
- [2] P. Braun-Munzinger, *Chemical Equilibration and the Hadron-QGP Phase Transition*, nucl-ex/0007021 (2000).
- [3] U. Heinz, *The little Bang: Searching for quark-gluon plasma in relativistic heavy-ion collisions*, hep-ph/0009170 (2000).
- [4] P. Koch, B. Müller and J. Rafelski, Phys. Rep. **142** (1986) 321.
- [5] M. Gaździcki and M. I. Gorenstein, Acta Phys. Pol. **B30** 2705 (1999).
- [6] S.V. Afanasev et al. (NA49 Collab.), CERN-SPSC-2000-035, ERN-SPSLC-P-264-ADD-7 (2000).
- [7] T. Matsui and H. Satz, Phys. Lett. **B178** (1986) 416.
- [8] H. Satz, *Colour Deconfinement in Nuclear Collisions*, hep-ph/0007069 (2000).
- [9] M. Gaździcki and M. I. Gorenstein, Phys. Rev. Lett. **83** (1999) 4009.
- [10] P. Braun-Munzinger and J. Stachel, Phys. Lett. **B490** (2000) 196.
- [11] J. Rafelski, Phys. Lett. **B62** (1991) 333.
- [12] M.I. Gorenstein, A.P. Kostyuk, H. Stöcker and W. Greiner, *Statistical Coalescence Model with Exact Charm Conservation*, hep-ph/0010148 (2000)

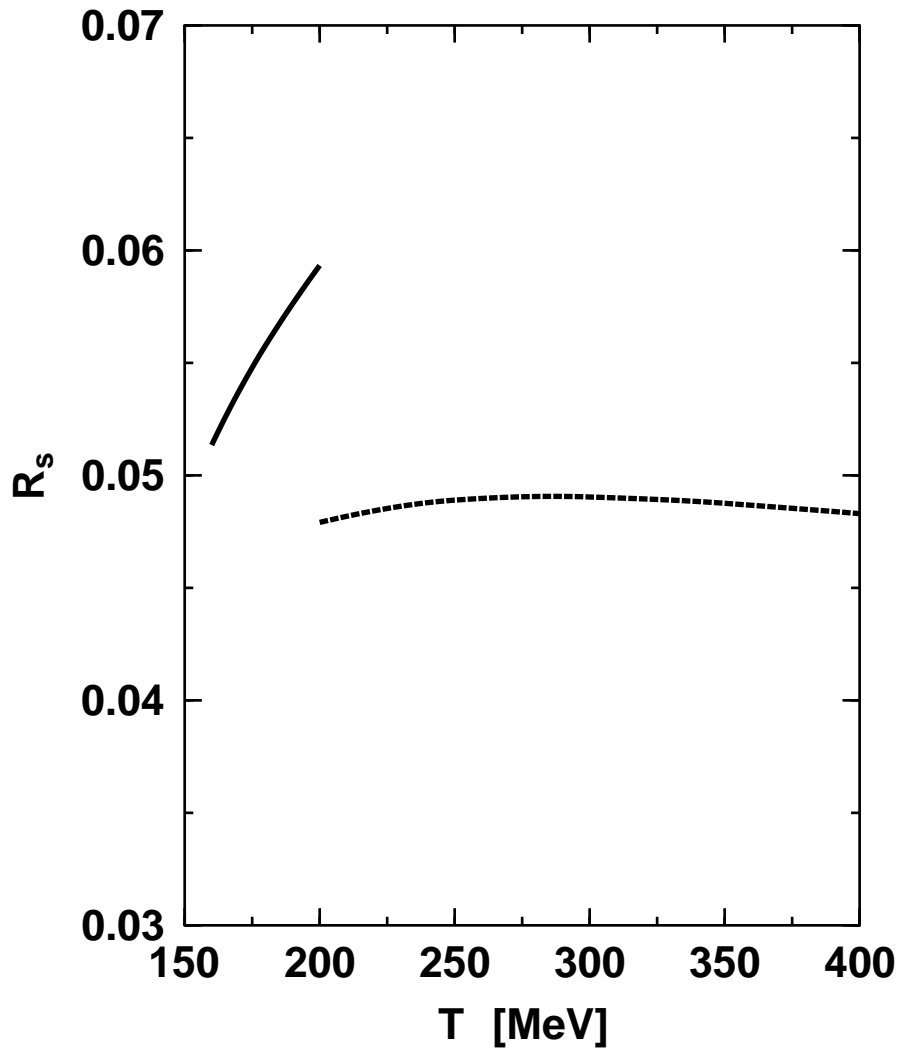


Figure 1: R_s (2) at $\mu_B = 0$ for the HG (solid line) and the QGP (dashed line).

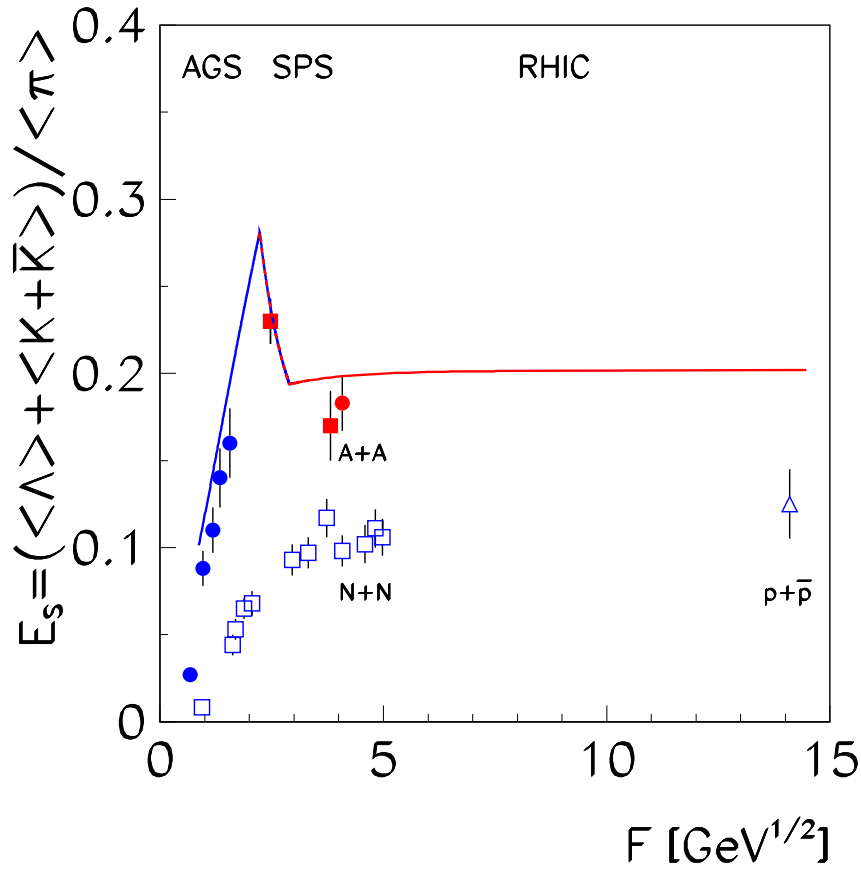


Figure 2: Collision energy ($F \equiv (\sqrt{s} - 2m_N)^{3/4}/\sqrt{s}^{1/4}$, \sqrt{s} is nucleon–nucleon c.m. energy) dependence of strangeness to pion ratio (1) for central A+A collisions (closed points), N+N and $p + \bar{p}$ collisions (open points). The prediction of the statistical model of Ref. [5] is shown by solid line. A transition to the QGP is expected between the AGS ($F \approx 2$) and the SPS ($F \approx 4$) energies and leads to the non-monotonic dependence of the strangeness to pion ratio. Preliminary data in Pb+Pb collisions at $E_{lab} = 40$ A·GeV [6] presented in the figure seems to support this conclusion. At high collision energies the ratio saturates at the value characteristic for equilibrium QGP.